ON THE THEORY OF DIFFUSION PUMP

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ABSTRACT. Attempt has been made, in this paper for an explanation of the successful functioning of the diffusion pump and experiments have been carried out in support of the theory. It has been observed that the partial pressure of the vapour of the pump filling in the vacuum chamber is much less than the vapour pressure of the fillings, which directly shows that the ultimate vacuum is independent of the vapour pressure of the filling. The ultimate vacuum, however, depends upon the degree of backstreaming at the jet, chiefly due to the imperfection of jet design. Further experiments have been done, which demonstrates the independence of partial pressure of air in vacuum chamber on the nature of pump filling The explanation of the working of multi-nozzle pump is suggested to be due to the gradual freeing of the oil in successive compartments from air contamination and also due to the more perfect stream-line flow of vapour in the upper jet

INTRODUCTION

The stage of perfection which the technique of diffusion pump has attained after thirty years of its invention by Gaede (1916) can give us today a vacuum which is well beyond the present measuring technique. The maximum vacuum which has been produced by Hickman (1940) passed the range of the ionization gauge and is claimed to be in the region of 10^{-10} mm. of mercury.

Despite the great advances in the technique of production of high vacuum by diffusion pumps, the mechanism of pumping is not yet understood very clearly, and a good deal of controversies remain on the basic question on the physical mechanism of the pumping process and the ultimate vacuum attainable by a diffusion pump. The choice of pump fluid attracted the attention of various workers in high vacuum technique, and mercury was recognised to be the ideal fluid for a long time until of late petroleum distillate oils (Apiezon types) and more recently synthetic oils (phthalates) have come to be used as suitable pump fluids.

The major question has been the dependence of the ultimate vacuum on the vapour pressure of the pump fluids. Some have held that the ultimate vacuum produced by a diffusion pump depends upon the vapour pressure of the fluid at the room temperature. For instance, Hickman reported that a mercury diffusion pump cannot get a vacuum better than the vapour pressure of mercury, without a trap. " It has been assumed since 1915 that the lowest pressure that can be attained by a vapour pump should correspond with the vapour pressure of the working fluid in the coldest part of the high vacuum side of the system. With mercury on a summer day, and in absence of a special cooling trap, this proves to be about 5×10^{-3} mm., agreeing well with theory."

On the other hand Gaede showed that even water can be used as a diffusion pump fluid. He was able to reduce the pressure from atmosphere down to 15 mm. of mercury by the use of a water diffusion pump, without the help of any backing pump. Backed by a water jet pump a three-stage water diffusion pump could produce X-ray vacuum. Further, we have the following quotation due to Langmuir (1916). " Maurice Leblanc showed that it is possible to get a vacuum of the order of 1 mm. of mercury in the condenser of a steam engine by using a steam injector." The vapour pressures of water at room temperatures of 10°, 20° and 30°C are 9.2, 17.5 and 31.8 mm. respectively.

If it is accepted that mercury diffusion pump cannot produce a vacuum better than the vapour pressure of mercury at room temperature (1.6×10^{-3} mm. at 20° C), one is confronted with the question as to how a mercury diffusion pump is successfully employed in laboratories to generate X-rays without any cold trap. Langmuir ovserved that there is no lower limit to which the pressure may be reduced by the diffusion pumps.

Discussing the question of ultimate vacuum attainable by a diffusion pump Newman (1925) expressed the view that not only the vapour pressure of mercury itself, but also the partial pressure of air contaminated with the mercury vapour jet was of primary importance. " Although the mercury vapour pressure may be a thousand times greater than the air pressure, the latter is continuously exhausted, due to the fact that diffusion of the gas depends solely on the ratio of the *partial* pressures of the gas, and not the *total* pressure of the vapour and gas. When the partial pressures are equal, diffusion ceases, but, as long as the stream of vapour is free from air, diffusion will not cease until the receiver is also free from air, and, as it is quite easy to produce a stream of air free vapour, the highest vacuum can be attained by this method ; in fact, a perfect vacuum should, *theoretically*, be attained." The italics are given by the author himself in the book.

Speed of Suction

If we examine the formulae used for the diffusion pump we find that they give only the speed of suction in relation to diffusion aperture, tube resistance, etc.

According to Gaede's formula, the speed of suction is given by

$$\frac{dv}{dt} = \frac{1}{l} \frac{\pi r^3}{2\eta_1} e^{-\frac{rP_1}{1520 d \eta_2}} \qquad \dots \quad (1)$$

where r = radius of the vacuum connecting line, or the diffusion aperture.

l = length of the line.

P_1 = vapour pressure of pump fluid at the jet.

η_1 = ' friction ' of gas (air) against the connecting line.

η_2 = ' friction ' of the vapour against the tube.

d = constant of gas diffusion.

The equation suggests that, when other conditions are the same, the speed of pumping is higher for the lower vapour pressure (P_1) of the fluid. The pumping action, according to this formula is continuous and asymptotic, and does not set any abrupt limit to it.

The formula, however, is complicated due to the factor containing the gaseous frictions and has not such a handy form as to admit of practical application. The more practical form now generally used is derived from the consideration of diffusion of gas through an aperture. If n_1 and n_2 be the number of molecules of a gas per unit volume on the two sides of the aperture, p_1 and p_2 their respective pressures, P_1 and P_2 their respective densities ($P_2 = n_1 m$ and $P_2 = n_2 m$), m the mass of each molecule, c the average velocity, the mass μ which passes through per unit area of the aperture per second is equal to the difference in masses which cross it both ways.

Thus, $$\mu = \tfrac{1}{4} n_1 mc - \tfrac{1}{4} n_2 mc$$

$$= \tfrac{1}{4} c (P_1 - P_2)$$

Since $$P = \frac{M}{RT} \quad \text{and } c = \sqrt{\frac{8RT}{\pi M}}$$

We have $$\mu = \tfrac{1}{4} \sqrt{\frac{8RT}{\pi M}} \cdot \frac{M}{RT} p_1 - p_2$$

$$= (p_1 - p_2) \sqrt{\frac{M}{2\pi RT}} \tag{2}$$

If we assume $p_2 = 0$ that is to say that the gas at p_1 is diffusing into a space with perfect vacuum we have

$$\mu = p_1 \sqrt{\frac{M}{2\pi RT}} \quad \ldots \quad (3)$$

But the mass of gas has its volume v under a pressure p_1 given by

$$v = \frac{\mu}{P_1} \quad \text{and} \quad P_1 = \frac{M}{RT} p_1$$

So that $$\mu = vP_1 = p_1 \sqrt{\frac{M}{2\pi RT}}$$

$$v = \sqrt{\frac{RT}{2\pi M}} \quad \ldots \quad (4)$$

Taking $R = 8.3 \times 10^7$, T = room temp. 300 K, and $M = 29$ for air we have the volume of escape of air by diffusion

= 11.7 litres per second per unit aperture

For a diffusion aperture A the rate of escape may be given by

= 11.7A litres per second ... (5)

For a diffusion pump, the diffusion aperture is taken for the annular aperture ('neck') round the vapour jet, through which the air is 'sucked.' The practical pumping speed, however, usually about 1/2 or 1/3 of the calculated speed, and the factor is sometimes known as the Ho coefficient (Ho, 1932).

Pumping Action

The essential point in this equation (4 or 5) also is the fact that it does not set any limit to the pumping action, and that it does not take into account the vapour pressure of the pump fluid.

We need a more critical analysis of this formula to justify its applicability, for a major objection might arise on the question that it has been assumed that the air is diffusing freely into a vacuum through the aperture, whereas we know that the space below the diffusion aperture contains copious vapour of the fluid and other gases (*e.g.* air) and we have set $p_2=0$ in equation (2) to get (3).

As a matter of fact we shall see that these are just the criteria for a perfect diffusion pump. In order that air may be 'sucked out' we shall have to provide a space with vacuum or lower pressure so that the air from the receiver may diffuse out. The vapour jet, if well designed, gives a stream of vapour all in the forward direction so that it has no component in the direction of the aperture. The 'pressure' of the jet is therefore 'zero' *in the direction* of the aperture, and hence it justifies putting $p_2=0$. Physically, the jet makes all the molecules (of vapour, air contamination, etc., from the jet) move away from the aperture so that diffusion takes place one way only, and whatever air molecules diffuse down into the vapour stream are caught and knocked on forward down to the backing pump.

Ultimate Vacuum

If all the vapour particles of the jet stream move in perfect stream line away from the diffusion aperture, air from the receiver would escape freely as indicated in equation (5). This would theoretically lead to any vacuum provided that sufficient time is allowed. But it is not possible to have a perfect jet (one not giving rise to turbulence), so that there is always a small fraction of vapour, mixed up with air, diffusing back through the neck of the pump.

The back-escape occurs not only due to the imperfection of the jet design, but also due to the pressure condition and condensation of the vapour below the jet. This is why a low vapour-pressure fluid would be preferable in order to avoid the accumulation of pressure and creation of turbulence in the body of the pump.

Taking back-diffusion into consideration the mass rate of escape through the neck would be given by

$$\eta=\tfrac{1}{4}n_1mc-\tfrac{1}{4}(n_2mc+n_vm_vc_v)$$

where n_1 = number of molecules of air per unit volume of the air above the neck (or receiver).

n_2 = the same for back-escaped air, and those with subscript v are those for back-diffused vapour.

We can omit the terms for the vapour as the vapour molecules can be removed by cold or charcoal traps. It is the back-escaped air which affects the vacuum really. Thus, considering the air on either side of the neck we find that the pumping action ceases when the partial densities or pressure of the gas equalise on either side (assuming uniform temperature at the neck). The amount of the back-escaped air depends upon several factors and does not necessarily equal the partial pressure of the oil vapour at the jet. In fact the pressure of the oil vapour would affect the vacuum. As the initial amount of air contamination, *i.e.*, partial pressure of vapour of the jet is difficult to measure, the difference is demonstrated indirectly. The vapour, for instance, does not manifest fully in the back diffusion. In an experiment with a mercury diffusion pump (Table II) the partial pressure of mercury vapour in the receiver was 4.8×10^{-4} mm. when the full (saturation) pressure for mercury at the room temperature would be 2×10^{-3} mm. Thus, in the dynamic condition, *i.e.*, when the pump is on, the receiver has not the full pressure of the jet vapour.

EXPERIMENT ON THE PUMPING MECHANISM AND ULTIMATE VACUUM

Fig. 1 shows the interior of an orthodox type of an oil diffusion pump which was constructed in this laboratory, and side tubes were attached to the nozzles to

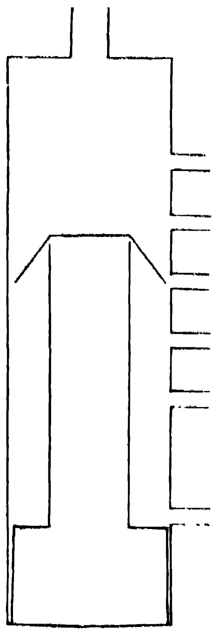

FIG. 1

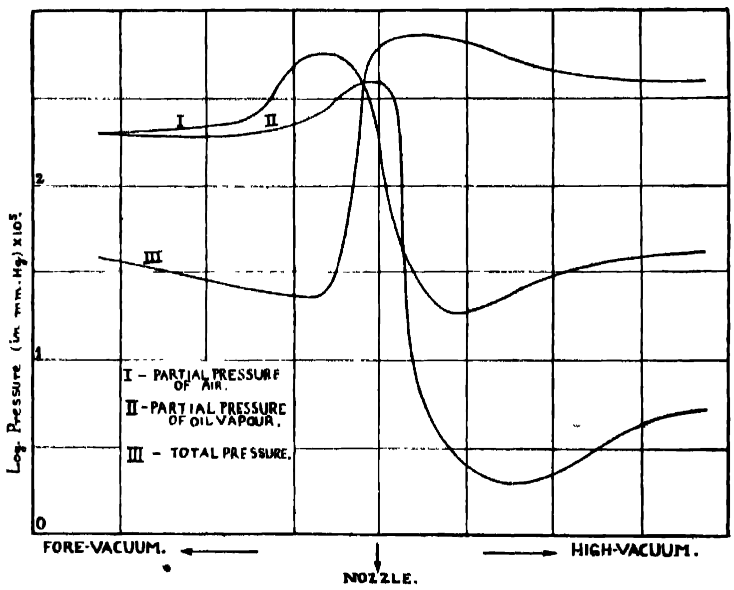

FIG. 2

study the pressure distribution inside the pump body. Table I and Fig. 2 show the result on the pressure distribution at different parts of the diffusion pump. It shows up the partial pressure of air (or CO_2, etc., all of which would behave as 'gas' to obey Boyle's law to appear in the compression column of the McLeod gauge), total pressure including vapour, and the vapour pressure by their difference. The Pirani gauge, calibrated across a liquid air trap, would record the vapour also when the trap is removed during the measurement of the total pressure.

TABLE I

Distribution of Pressure (mm. Hg.) *inside a Single Stage Oil Diffusion Pump*

Positions of tappings relative to vapour jet	Pressure measured by McLeod Gauge (Partial pressure of air).	Pressure measured by Pirani Gauge (Total pressure)	Partial pressure of oil vapour (Difference of Cols 2 & 3)	Ratio of vapour pressure to air pressure = col. 4/col. 2
1	2	3	4	5
1. 7.0 inch above jet	5.0×10^{-5}	4.0×10^{-4}	3.5×10^{-4}	7
2. 3.0 inch above jet	2.0×10^{-5}	2.6×10^{-4}	2.4×10^{-4}	12
3. 1.5 inch above jet	3.0×10^{-5}	2.3×10^{-4}	2.0×10^{-4}	6.6
4. At the jet	4.0×10^{-3}	6.0×10^{-3}	2.0×10^{-3}	0.5
5. 1.5 inch below jet	2.5×10^{-3}	8.6×10^{-3}	$.5 \times 10^{-3}$	2.2
6. 3.0 inch below jet	2.0×10^{-3}	5.0×10^{-3}	3.0×10^{-3}	1.5
7. 6.5 inch below jet, at backing pump nozzle	2.0×10^{-3}	4.0×10^{-3}	2.0×10^{-3}	1.0

TABLE II

Vacuum Produced by a Three-Stage Mercury-Diffusion Pump (in mm. Hg.)

Measured by McLeod Gauge	Measured by Pirani Gauge	Partial pressure of Hg difference of 1&2	Vap. pressure of Hg at room temp 26°C	Ratio of back diffusion of Hg. vap	Ratio of total pressure to Sat. Vap. pressure of Hg.
1	2	3	4	5	6
2×10^{-4}	5×10^{-4}	4.8×10^{-4}	2×10^{-3}	0.16	0.167

Table I gives the pressure distribution inside a diffusion pump and shows the compression effect below the jet. The maximum pressure occurs at and just below the jet. Column 4 shows that the back diffusion of the vapour differs according to the vacuum condition and remains below the saturation pressure (as it cannot go above it). This point is more clearly shown in Column 5 of Table II in the case of mercury.

Table II shows that a mercury diffusion pump can reduce the pressure, even without a trap, lower than the vapour pressure of mercury at room temperature. Both the partial pressure of air and the back-diffused vapour go far below the saturated vapour pressure of mercury.

INDEPENDENCE OF ULTIMATE VACUUM WITH VAPOUR PRESSURES OF FLUIDS

That the evacuation of air is almost independent of the vapour pressure has been demonstrated by the use of different fluids in a diffusion pump (Ray and Sengupta, 1945). Five kinds of pump fillings were tried, namely, Apiezon oil B, Capella oil D (Caltex Co), Petroleum jelley (white) and solid paraffin, and all of them gave the same minimum pressure (Table III) with certain adjustments, chiefly heat input and jacket cooling.

TABLE III

Effect of Pump Fluids on the Production of Vacuum by a Single Stage Diffusion Pump

(Pressure in $\mu = 10^{-3}$ mm. Hg.)

Pump filling	Vacuum conditions		Relative heat input (Tentative estimate)	REMARKS
	Partial pressure of air	Partial pressure of fluid vapour*		
1. Apiezon Oil	0.03	0.10	1	
2 Capella D (Caltex)	0.03	0.17	1.5	
3. Mobil B	0.03	0.07	1.5	—
4 Petroleum Jelly (White)	0.03	0.67	2	Water circulation is to be low enough to maintain fluidity and adequate boiling.
5. Solid Paraffin	0.03	0.57	2.5 to 3	Do.

*This is however not the true vapour pressure of the fluid under static saturation condition, as the pressure is measured under constant pumping condition.

The Fractionating Pump

The advantage of Hickman's self-fractionating pump was also investigated in the light of the picture we put forward. The fractionating pump with three compartments gave a good performance not as regards as the suction of air but regarding the back escape of the fluid used, solid paraffin was tried in this pump and the back-escaped vapour pressure was found to be 0.36μ as compared with 0.6μ with a single stage diffusion pump of the otherwise same design. The partial pressure of air however remained the same at °0 3μ in both cases The phenomenon can be explained by the idea of forward stream line flow of vapour, which is facilitated by the successive vapour jets, making the upper jets more and more stream-line. The total pressure in the vacuum chamber could thus be much reduced by the use of a multi-jet pump without the help of a special trap.

DISCUSSION

The foregoing experiments suggest that it is necessary to define the 'vacuum' in distinct terms of the 'partials', *viz.*, 'partial pressure of the air left in the chamber' and the partial of the back-escaped vapour of the pump fluid

The results of the experiments shows that air pressure can be pumped down much below the vapour pressure of the fluid and the partial pressure of the escaped vapour is also much less than the saturated vopour pressure under the room temperature. The success of the diffusion pump depends largely on the jet design to give a stream line flow directed away from the diffusion aperture.

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